ESTIMATION OF VERTICAL AIR MOTIONS IN DESERT TERRAIN FROM TETROON FLIGHTS

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ABSTRACT

Low-level, constant volume balloon (tetroon) flights made from Yucca Flat in the Nevada Proving Grounds of the Atomic Energy Commission are utilized to yield an estimate of the nature and magnitude of vertical air motions in desert areas. It is found that during the day the tetroons oscillate as much as 10,000 feet in the vertical with vertical velocities often exceeding 5 kt., whereas during the night the vertical oscillations are on the order of 100 feet and vertical velocities seldom exceed 0.5 kt. There are indications that during the day, at this particular site, helical circulation patterns exist with axes parallel to the north-south oriented valley floor and with alternating circulation sense across the valley, while during the night the small vertical oscillations are more nearly tied to the local topography. Pure mountain influences on the tetroon trajectories could not be clearly delineated owing to the tremendous vertical oscillations associated with solar heating.

1. INTRODUCTION

The constant volume balloon (tetroon) flights previously reported on by the writers were launched from coastal radar sites at Cape Hatteras [1] and Wallops Island [2], and most of the tetroon trajectories lay over water. As the sea surface presents a fairly homogeneous surface with respect to radiative and frictional influences, it is not surprising that most of these tetroon flights (at least those that were reliably positioned) appeared to remain very nearly at constant level, the exception being two flights which were released within, or close to, a cold frontal zone [2]. Because one of the chief uncertainties with respect to these superpressured tetroons is the degree to which they respond to vertical air motions, it was thought desirable to make some tetroon flights in desert regions where the vertical air motions would be at a maximum. Consequently, during September 1960, 15 tetroon flights were made from Yucca Flat in the Nevada Proving Grounds of the Atomic Energy Commission. The tetroons were tracked and positioned by means of the newly acquired and modified M-33 radar of the Weather Bureau's Las Vegas Research Station. This paper presents some results obtained from this series of flights, with emphasis on the nature and magnitude of the vertical air motions indicated by the tetroons.

2. PREVIOUS WORK WITH NEUTRAL BALLOONS

Several meteorological groups have used neutral or no-lift pibal balloons to estimate vertical air motions near the earth's surface. Probably the most extensive use of this technique was at Oak Ridge, Tenn. between January 1949 and February 1950, as reported by Gifford [5]. Gifford also cites German work along this line, in particular the work of Lange [8] in connection with gliding activities.

Superpressured, constant volume, Mylar balloons (tetroons) offer some advantages with respect to no-lift pibal balloons, particularly for the determination of vertical air motions. These are:

1. The tetroon, being for all practical purposes nonextensible, will not undergo a change in buoyancy force due to variation in balloon volume associated with heating effects, as will the pibal balloon. In particular, tetroons superpressured to 50–100 mb. have the capability of going through sunrise and sunset without change in flight altitude, although this capability has not yet been utilized.
2. The tetroon can, within certain limits, be set to float at a given altitude, whereas the no-lift pibals must, by their nature, be set to float close to the earth's surface.
3. The radar-reflective tetroon can be tracked to greater distances than can no-lift pibals by double theodolite methods, and furthermore tetroon tracking can be accomplished in clouds, at night, etc.

These advantages make it worthwhile again to carry out experiments whose aim is the delineation of 3-dimensional air trajectories. In the following, comparison is often made between the no-lift pibal data of Gifford and the tetroon data obtained at Yucca Flat.

3. FLIGHT PROCEDURES AND DATA OBTAINED

Table 1 shows the time of tetroon release, the flight equipment utilized, the flight level, duration of flight,

*Research undertaken as portion of programs sponsored by Reactor Development Division, Atomic Energy Commission, and Air Pollution Division, Public Health Service.

TABLE 1.—*Tetroon flights from Yucca Flat*

Flight	Date	Launch site	Launched (PST)	Average flight altitude (feet)	Duration at flight altitude (minutes)	Distance tracked at altitude (n. miles)	Equipment	Termination due to—
1	9-19-60	Radar	1213	6200	70	10.3	42″ T, CR	Radar lost contact.
2	9-19-60	Radar	1346	4100	48	6.7	42″ T, 2 CR	Grounded.
3	9-19-60	Radar	1506	3100	58	7.9	42″ T, 2 CR	Radar lost contact.
4	9-19-60	Radar	1749		0	0.0	42″ T, 2 CR, L	Radar lost contact.
5	9-19-60	Radar	1855	1000	15	1.9	42″ T, M, L	Radar lost contact.
6	9 19-60	Radar	2008	160	56	6.1	60″ T, 2 CR, L	Radar lost contact.
7	9-20-60	Radar	0635	1200	101	2.8	60″ T, 2 CR, M	Grounded.
8	9-20-60	Radar	0938		0	0.0	60″ T, CR	Burst.
9	9-20-60	Yucca Wx. Sta	1204	3500	81	15.3	60″ T, 2 CR	Radar lost contact.
10	9-20-60	Yucca Wx. Sta	1456	4200	50	13.2	60″ T, 2 CR	Behind hill.
11	9-20-60	Yucca Wx. Sta	1813		0	0.0	60″ T, 2 CR, M, L	No radar contact.
12	9-20-60	Radar	1925		0	0.0	60″ T, 2 CR, M, L	Caught in power line.
13*	9-20-60	Radar	2036	150	44	2.8	60″ T, CR, M, L	Radar lost contact.
14**	9-21-60	Radar	0702	6300	52	25.3	60″ T, CR, M	Behind hill.
15	9-21-60	Yucca Wx. Sta	0851	2800	64	18.9	60″ T, M	Behind hill.

*Immediately after release, momentarily caught in power line and grounded.
**Towed aloft by radiosonde balloon.

Equipment: T=tetroon, CR=corner reflector, M=radar reflective mesh, L=pibal light.

and other information of possible interest. Flight termination was due to grounding of the tetroon, disappearance of the tetroon behind the mountain ridges surrounding Yucca Flat, and (most often) loss of radar contact with the tetroon as it approached a mountainside due to the appearance of terrain echoes in the radar gate. It is seen from table 1 that reasonably long-range trajectories could be obtained only for flights at relatively high level or for flights released upwind from the radar site.

The positioning accuracy of the M–33 radar is not known with certainty. It has been estimated [3] that the average error in azimuth and elevation angle is about 2 mils (0.11 degrees), leading to height and lateral displacement errors of about 100 feet at ranges near 50,000 feet. The very accurate FPS–16 radar utilized at Wallops Island gave errors of less than 10 feet at such ranges. However, the loss of accuracy in the M–33 is partially offset by its mobility, simplicity of operation, and by the fact that a much smaller crew (2 men) can handle it.

As a consequence of the above positioning errors, at Yucca Flat the tetroon velocity was determined as an average over 1-minute intervals rather than the 30-second intervals utilized on the Wallops Island flights. The horizontal velocity data were derived from dial readings giving tetroon slant range in yards and azimuth angle in mils. However, the digital elevation angle data could not be obtained conveniently owing to the position of the dial and therefore the tetroon height was scaled directly from the plotboard. From the change in tetroon slant range, azimuth angle, and height with time, values of the longitudinal (V_s), transverse (V_n), and vertical (w) velocity components were obtained.

4. TETROON TRAJECTORIES

Figure 1 shows the horizontal trajectories of the 12 successful tetroon flights. The tetroons were released from the radar site and from Yucca Weather Station about 7 miles to the south. The trajectories are based upon tetroon positions every minute but for simplicity in the figure the positions are indicated only at 5-minute intervals. For the sake of clarity, the surface topography has also been traced only at 1,000-foot intervals.

The few tetroon trajectories available suggest the existence of preferred corridors of escape for air flowing northward up Yucca Flat during the midday hours, with one corridor extending northward from Whiterock Spring (as illustrated by the trajectories of flights 1 and 9) and the other corridor extending northward from Oak Spring (as illustrated by the trajectories of flights 14 and 15). A priori, one would not expect that the air flow at such heights (3,000–6,000 feet above the earth's surface) would be influenced by terrain during the hours of daytime instability, and indeed smoke experiments have shown no evidence for such a channeling effect. The evidence for such an effect from the few tetroon data is sufficiently strong, however, to warrant a test series of serial tetroon releases in order to confirm whether or not tetroons released from the given area will ever traverse the highlands between Whiterock Spring and Oak Spring. Note that flight 2 grounded on a spur in this region, suggesting both an unwillingness for air parcels to ascend over these highlands and an uncertainty with regard to which of the above suggested corridors to take.

Possibly associated with the existence of preferred corridors of escape is an intriguing tendency for the azimuth of the end point of the tetroon trajectories to shift regularly in a clockwise sense during the afternoon hours. This tendency is shown in figure 2 by the dots. A regression line, fitted to the afternoon azimuths, indicates an azimuth turning of 9 degrees per hour, precisely the pendulum-day period at this latitude. It is not certain whether this result is coincidental or not. During times of sea breeze, low-level winds obtained from anemometers often turn

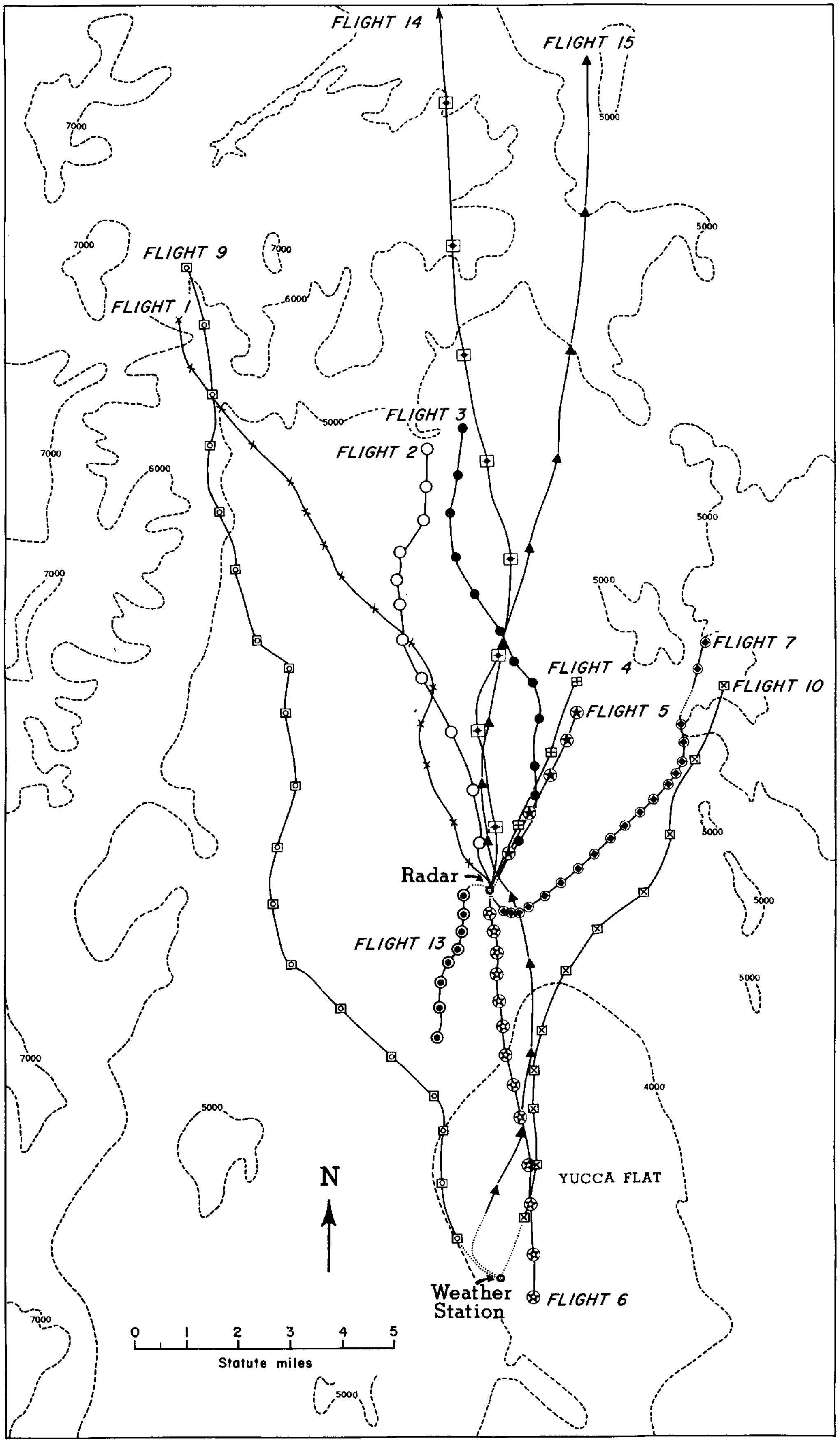

Figure 1.—Trajectories of the 12 successful tetroon flights at Yucca Flat, Nevada Proving Grounds. Tetroon positions indicated at 5-min. intervals, ground height (dashed lines) at 1000-ft. intervals. Dotted segments of trajectories estimated from visual sightings.

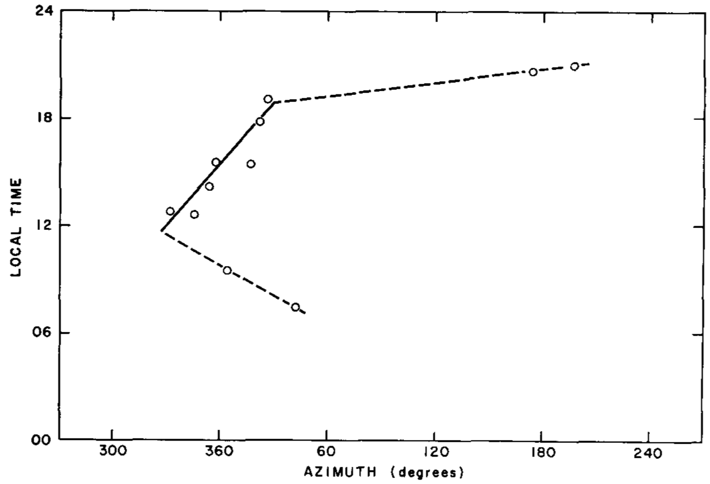

Figure 2.—Azimuths of end points of tetroon trajectories (dots) as function of mid-time of flight. A regression line (solid line) is fitted to the afternoon azimuths.

with approximately a pendulum-day period [4] and also the Eulerian-type winds obtained from various sites in Yucca and Jackass Flats indicate a somewhat similar change with time [12]. The tetroon data suggest that these wind-direction changes with time extend to quite high elevations and may not be purely local in nature.

Two of the tetroon flights (6 and 13) went southward down Yucca Flat, embedded in the nighttime drainage flow. Flights 4 and 5 were released early in the evening in an attempt to catch the transition from daytime upslope to nighttime drainage flow, but unfortunately both flights were lost by the radar as they approached the mountainside. In any event the shift might never have been detected from these flights because of the probability that the height of the tetroons above the earth's surface exceeded the depth of the drainage flow during such an early stage of development. In a sense flight 7 detected the transition from drainage to upslope flow with the flight starting out to the southeast and then curving counterclockwise and passing out of the Flat to the northeast. In the following the flights are grouped and discussed according to whether they took place near midday, during early morning or evening, or during the transition period.

5. TETROON HEIGHT FLUCTUATIONS NEAR MIDDAY

Figure 3 shows tetroon height as a function of range for the five flights (1, 2, 3, 9, 10) released during the early afternoon. The essentially north-south height profiles have been positioned relative to the radar site in order that any tendency for similarity among the height traces might be noted. In this case there is only the weakest sort of evidence for ascending motion upstream from the radar, descending motion immediately downstream from the radar, and ascending motion about 30,000 ft. downstream from the radar. Note that in figure 3, and in subsequent figures of this type, the horizontal and vertical scales are identical so that the trajectory slope in the longitudinal-vertical plane is obtained immediately. This slope exceeds 30 degrees for long distances along many of these afternoon trajectories. This is the order of streamline slope found by glider pilots in mountain-wave regimes [13].

The magnitude of 1-minute-average vertical velocities derived from these five afternoon flights is shown in figure 4. Nearly one-fifth of the time the absolute magnitude exceeds 5 kt., with some evidence that in the mean the ascending motions are of greater magnitude than the descending motions. On several occasions the vertical velocity of the tetroon exceeded its horizontal speed.

Table 2 gives an estimate of the average trajectory wavelength and period (in the longitudinal-vertical plane) for each afternoon flight. It is emphasized that these represent Lagrangian scales and do not necessarily yield the length and period appropriate to a streamline pattern. While the wavelengths and periods are difficult to delineate and some subjectivity is undoubtedly involved, basically the wavelengths are on the order of 5–10 mi. and the periods of vertical oscillation are on the order of 30–45 min. By comparison, the Oak Ridge no-lift pibal data of Gifford suggested wavelengths and periods on the order of 5,000 ft. and 15 min. under conditions of strong instability and light wind speed, and wavelengths and periods on the order of 15,000 ft. and 25 min. under conditions of moderate instability and strong wind speed. Thus the period of oscillation in the longitudinal-vertical plane is about twice as great at Yucca Flat as at Oak Ridge while the wavelength is about four times as great.

There exists a "natural" period of air parcel oscillation in the vertical [7, p. 132], which period is infinite for a dry adiabatic lapse rate and is about 10 minutes for the lapse rate (0.7° C./100 meters) usually prevailing in the atmosphere. Both the Wallops Island tetroon flights and the Brookhaven no-lift pibal flights of Gifford [6] indicate a period of oscillation in the vertical somewhat smaller than 10 minutes for the given stability, in rough agreement with the "natural" period. The 40-minute periodicity derived from the Yucca Flat flights would correspond to the "natural" period only if the lapse

Table 2.—*Lagrangian wavelength and period of vertical oscillation for early afternoon tetroon flights from Yucca Flat*

Flight	Wavelength (feet)	Period (minutes)
1	42,000	45
2	26,000	30
3	35,000	40
9	43,000	35
10	51,000	42
Average	39,000	38

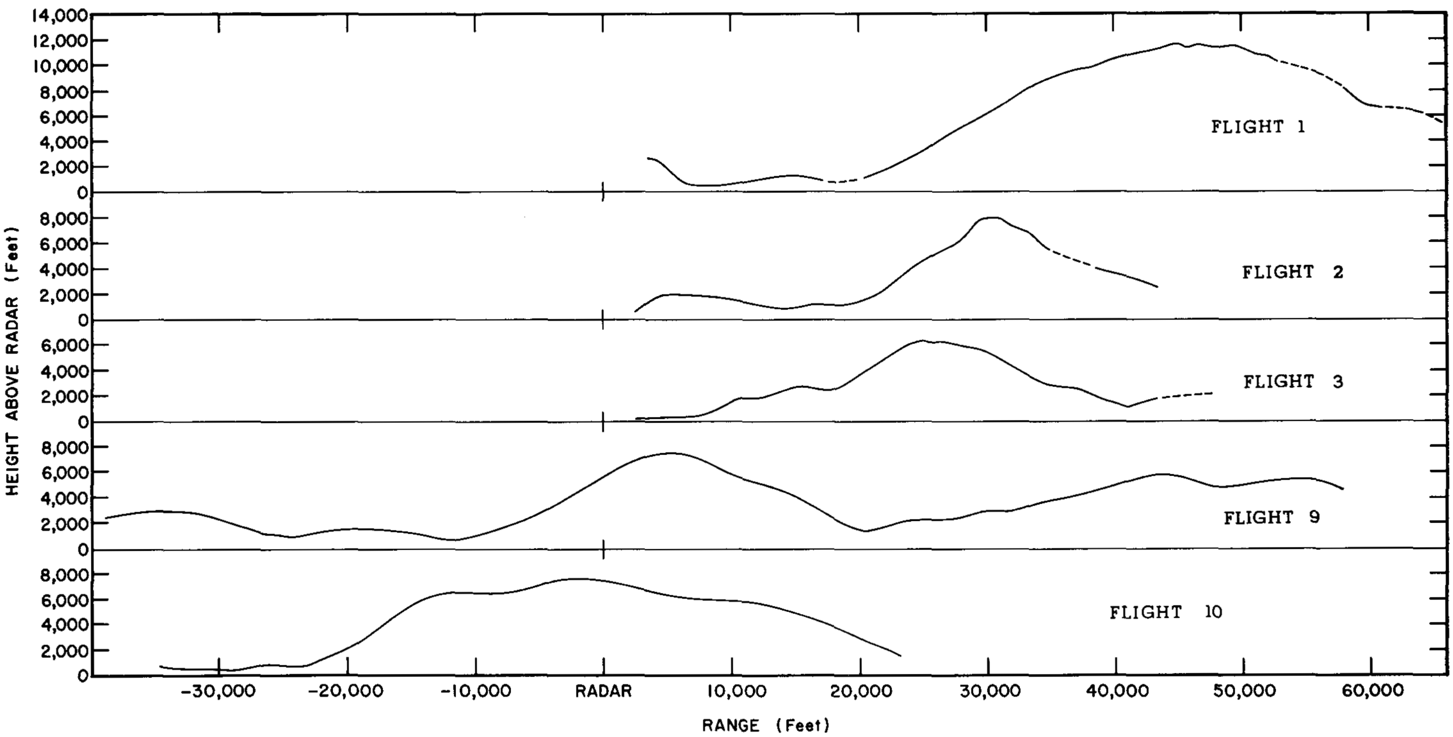

Figure 3.—Tetroon height versus distance along trajectory for early-afternoon flights (1, 2, 3, 9, 10) at Yucca Flat. Dashed lines represent interpolated heights.

rate at Yucca Flat during the time of the flights was within 0.02° C./100 meters of the dry adiabatic lapse rate. Both the Las Vegas and Jackass Flat soundings do indeed show that the lapse rate is very close to the dry adiabatic at the time of these flights, with a superadiabatic lapse rate close to the ground followed by an approximately dry adiabatic lapse rate up to at least 10,000 feet. Thus there is a suspicion that the height fluctuations experienced by tetroons and no-lift pibals may be attuned to a period specified by the existing lapse rate.

With regard to the fidelity with which tetroons follow the vertical air motion, it is of interest to compare the height which air parcels might be expected to attain during the heat of the afternoon (mixing depth) with the height attained by the tetroons. Figure 5 shows early morning (0300 PST) radiosonde soundings for Jackass Flat, some 20 miles to the southwest of Yucca Flat. The dashed lines in this figure represent dry adiabats drawn through surface temperature readings at Yucca Flat during the time of flights 1, 2, and 3 on September 19, flights 9 and 10 on September 20, and flight 15 on September 21.

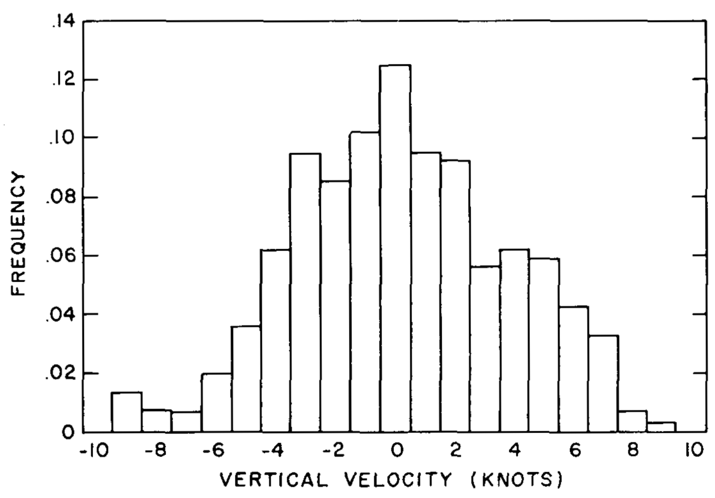

Figure 4.—Frequency distribution of 1-minute-average vertical velocities derived from five early-afternoon tetroon flights.

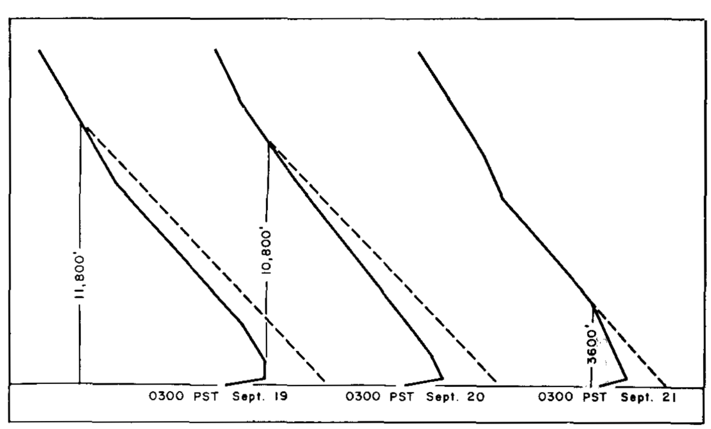

Figure 5.—Early-morning radiosonde soundings at Jackass Flat, Nevada Proving Grounds. Dashed lines represent dry adiabats through surface temperature readings at Yucca Flat during times of tetroon flight.

TABLE 3.—*Comparison of maximum tetroon height and air parcel mixing depth for daytime tetroon flights from Yucca Flat*

Flight	Maximum tetroon height (feet)	Mixing depth (feet)
1	11,700	11,800
2	7,900	11,800
3	6,300	11,800
9	7,600	10,800
10	7,700	10,800
15	5,800	3,600
Average	7,800	10,100

The flat temperature maximum at this locality enables a single temperature to represent conditions during more than one flight. Presumably, one would anticipate rather free vertical mixing during the afternoon up to the height where the dry adiabats intersect the sounding curves. Actually, since a superadiabatic lapse rate prevails near the earth's surface in this region during the daytime hours, the mixing depth would be somewhat less than that indicated by the given intersection. Table 3 gives a comparison between the mixing depth so obtained and the maximum height attained by the tetroons. While there is good agreement on some of the flights and poorer agreement on other flights, there is a suggestion that basically the tetroons were oscillating in the vertical through a layer of air which one would expect to be in a mixed condition. This represents evidence that the tetroons were following the vertical air motions to a considerable degree. Apparently, the restoring force acting to displace the tetroons back to their equilibrium density surface is small compared to the drag force acting on the tetroons through the agency of large vertical motions.

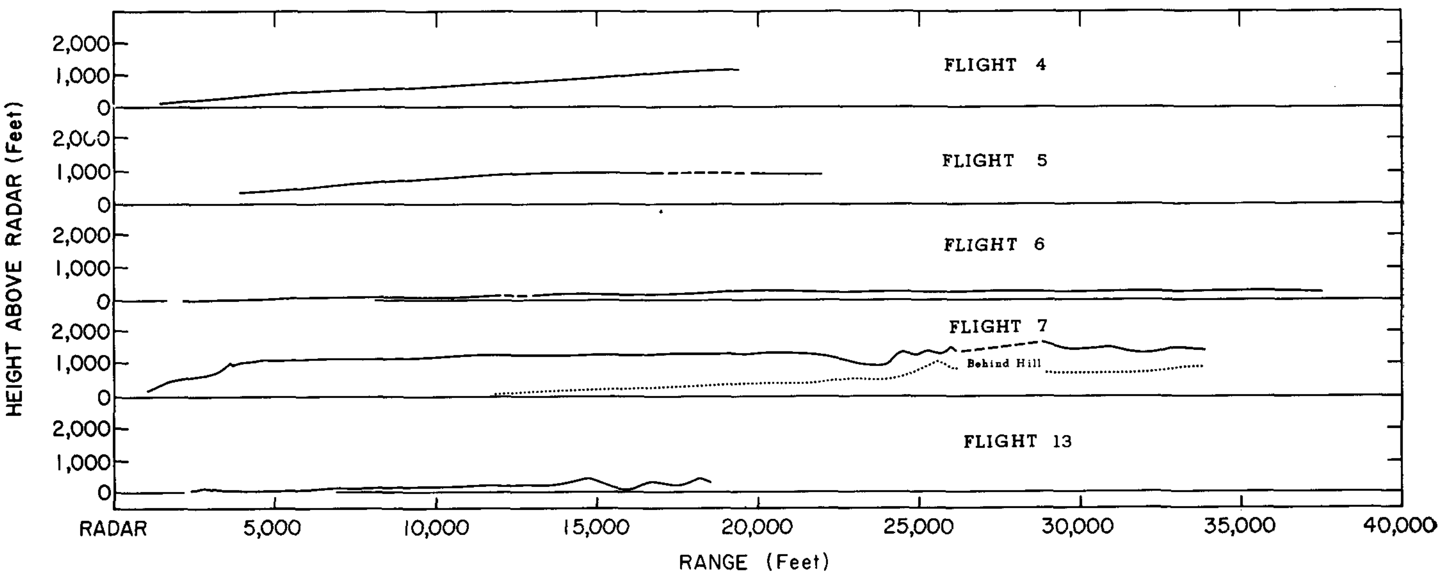

FIGURE 6.—Tetroon height versus distance along trajectory for early morning and evening flights (4, 5, 6, 7, 13) at Yucca Flat. Dashed lines represent interpolated heights. Dotted line indicates surface topography along flight 7.

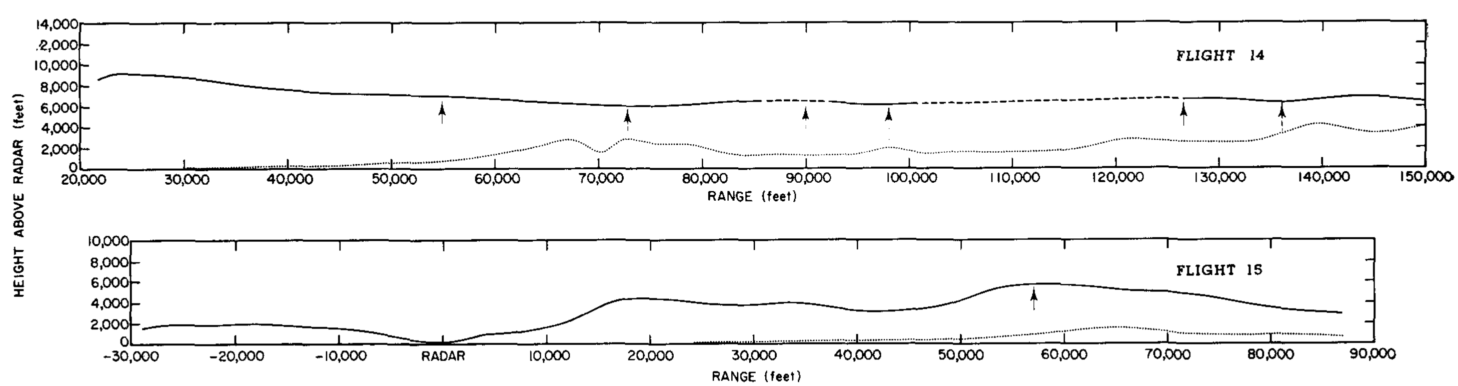

FIGURE 7.—Tetroon height versus distance along trajectory for morning flights (14 and 15) at Yucca Flat. Dashed lines represent interpolated heights, dotted lines indicate surface topography along flights, and solid and dashed arrows indicate positions of maximum and minimum tetroon height.

6. TETROON HEIGHT FLUCTUATIONS AT NIGHT

Figure 6 shows tetroon height as a function of range for the five flights (4, 5, 6, 7, 13) released during the evening and early morning hours. Presumably, these flights are reasonably representative of flight conditions during nighttime. The difference in magnitude of tetroon oscillations in the vertical at night and near midday is striking indeed, with vertical oscillations in the former case on the order of 100 ft. and in the latter case on the order of 1,000–10,000 ft. Furthermore, in contrast to the results presented in figure 4, 84 percent of the 1-minute-average vertical velocities derived from these five flights were within the range −0.5 to 0.5 kt.

The two flights released latest in the evening (flights 6 and 13) flew no higher than 300 and 600 ft. above the ground, respectively, apparently within an inversion surface. It is assumed, therefore, that the vertical oscillations experienced by these flights to some extent mirror the undulations in the inversion surface. Although flight 6 closely followed the contour of minimum height in the valley floor whereas flight 13 followed the contour of 4,080 ft. somewhat to the west, along both flights, in general, the tetroon height slowly and regularly increased with time suggesting either that the inversion surface rises as one moves southward down the Flat or that at this time in the evening there is an increase in inversion height with time. The possibility that the tetroons did not reach their equilibrium altitude is made unlikely by previous experience concerning the length of time it takes tetroons to attain that altitude. The use of tetroons as an inversion-surface tracer (in the Los Angeles Basin, for example) is immediately suggested.

Other than the slow increase in tetroon height with time noted along flights 6 and 13, little in the way of regular height fluctuations was noted on these nighttime flights. The rather large, but intermittent height fluctuations along flight 7 will be considered in relation to mountain effects in the following section.

7. INFLUENCE OF TOPOGRAPHY UPON TETROON HEIGHT

One of the features it was hoped could fairly easily be investigated by means of tetroon flights in the Yucca Flat region was the air flow over mountainous terrain. However, since many of the tetroon flights were confined to Yucca Flat itself and, moreover, since most of the flights were made during the daylight hours when the vertical tetroon oscillations associated with solar heating far outweighed any vertical oscillations associated with topography, the results were disappointing. The only flights suitable for consideration here were those released early enough in the morning to avoid the bulk of the thermal influences and yet which crossed mountain ridges of appreciable size (flights 7, 14, and 15).

The topography along flight 7 has been plotted in figure 6. This flight traversed a mountain pass and subsequently disappeared behind a hill for over 10 minutes before again being picked up by the radar. The interesting thing is that while this flight was stabilized at a level sufficiently high to avoid an upcoming mountain ridge, upon passing a small hill of no more than 100-foot height, the tetroon descended 400 feet to a level below the ridge. It is suggested that this tetroon descent was induced by descending air motion associated with a hillside slope not yet illuminated directly by the early morning sun. Subsequently the tetroon ascended quite rapidly (400 ft. in 2 min. or at a speed of 2 kt.) to a height sufficient to clear the upcoming ridge. This sudden ascent took place about 2,000 ft. upwind of the ridge itself and as it could hardly have been thermally induced, must have been a purely mechanical consequence of the presence of the mountain ridge.

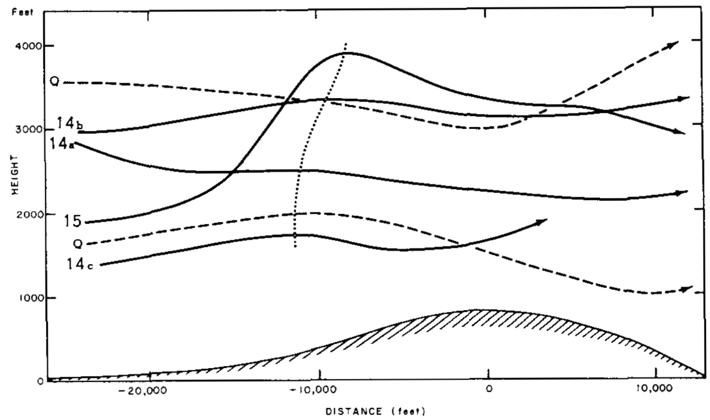

Figure 8.—Portions of trajectories of flights 14 and 15 (solid lines) in the longitudinal plane and their relation to a schematic mountain ridge. The dashed lines represent streamlines deduced theoretically by Queney for medium-sized mountains. Dotted line is locus of maximum tetroon heights.

Figure 7 shows the topography and tetroon height traces along flights 14 and 15. The arrows in this figure indicate places of maximum (solid arrows) and minimum (dashed arrows) tetroon height. In the case of flight 14, which was towed aloft by a radiosonde balloon and flew at an altitude amenable to rather lengthy tracking, the tetroon traversed several mountain ridges of varying size. However, the tow release on flight 14 did not function at the proper altitude with the result that the tetroon, upon release, slowly sank to its design altitude, making the delineation of mountain influences over the initial ridge somewhat difficult. On flight 15 there was a pronounced tetroon ascent a little upstream from the main mountain ridge. On the one hand it would be easy to associate this ascent with air flow over the ridge. On the other hand, since the tetroon had previously undergone a similar rise while over Yucca Flat itself, such an association may be erroneous.

In figure 8 are plotted the height traces (solid lines) along flights 14 and 15 as a function of position with respect to the nearest mountain ridge. The dotted line shows that in all cases the maximum tetroon height was reached upstream from the ridge with the distance upstream being on the order of two times the height of the mountain. For comparison we have scaled down and plotted, in the same figure, streamlines (dashed lines) deduced theoretically by Queney [10] for a mountain of medium size. The tetroon height traces agree better with the low-level Queney streamline than with the high-level one. However, it will be apparent to the reader that while the tetroons may have a great potential for the study of air flow over mountains, these particular flights were not ideally suited for such investigations. Consequently this comparison of observed and theoretical streamlines and trajectories will not be carried further.

8. TETROON CIRCULATIONS IN THE TRANSVERSE PLANE

In order to illustrate the nature of tetroon circulations in the transverse plane, a straight line was drawn between initial and final tetroon position at flight altitude and deviations in height and lateral distance from this line were computed at minute intervals. Figure 9 shows these transverse circulations (looking downstream, or northward, up the Flat) for the five afternoon flights. Once again the tetroon positions are indicated at 5-minute, instead of 1-minute, intervals for clarity. It is seen that basically the transverse tetroon circulations have the same vertical and lateral dimensions with an average eddy diameter in the transverse plane of about 5,000 ft. At Oak Ridge, Gifford found eddies of 700-ft. diameter in this plane, nearly an order of magnitude smaller than that found at Yucca Flat.

Flights 2, 9, and 10 possess a clockwise circulation in the transverse plane whereas flights 1 and 3 possess a counterclockwise circulation in this plane. Figure 9 shows the manner in which the flights were ordered across the Flat, from the flight that went farthest to the west (flight 9) to the flight that went farthest to the east (flight 10). It is seen that when the flights are ordered in this way the sense of the transverse circulation alternates so that there is agreement among the flights as to the position of upward and downward motion. Thus, although it appears unlikely that systematic circulation patterns could be maintained for a period of hours in such a region of intense circulation, the possibility at least exists that the air circulation in Yucca Flat consists of a series of helices, perhaps fixed with respect to terrain features, with axes running approximately north-south. Figure 10 shows the vertical motion pattern which results when an attempt is made to draw to the vertical velocity data, obtained from the five afternoon tetroon flights, with such helical circulation in mind. The axes of the helices, or longitudinal rolls, are spaced 15,000–25,000 ft. apart and are positioned in such a way that the ascent portion of the helical circulation occurs over the western extremity of the Flat but apparently not over the eastern extremity.

It should be emphasized at this point that the vertical motion pattern derived from the five afternoon flights, and presented in figure 10, is not unique. Along the line of the discussion in Section 4, the vertical motion pattern could also be drawn in the form of transverse rolls oriented across Yucca Flat, as in figure 11. The pattern in figure 11 appears as reasonable as that presented in figure 10; in fact, most meteorologists, if simply handed the data, would probably analyze them in the form presented in figure 11. The question now arises, which of the circulation patterns (assuming persistence for either pattern) presented in figures 10 and 11 is the more basically correct,

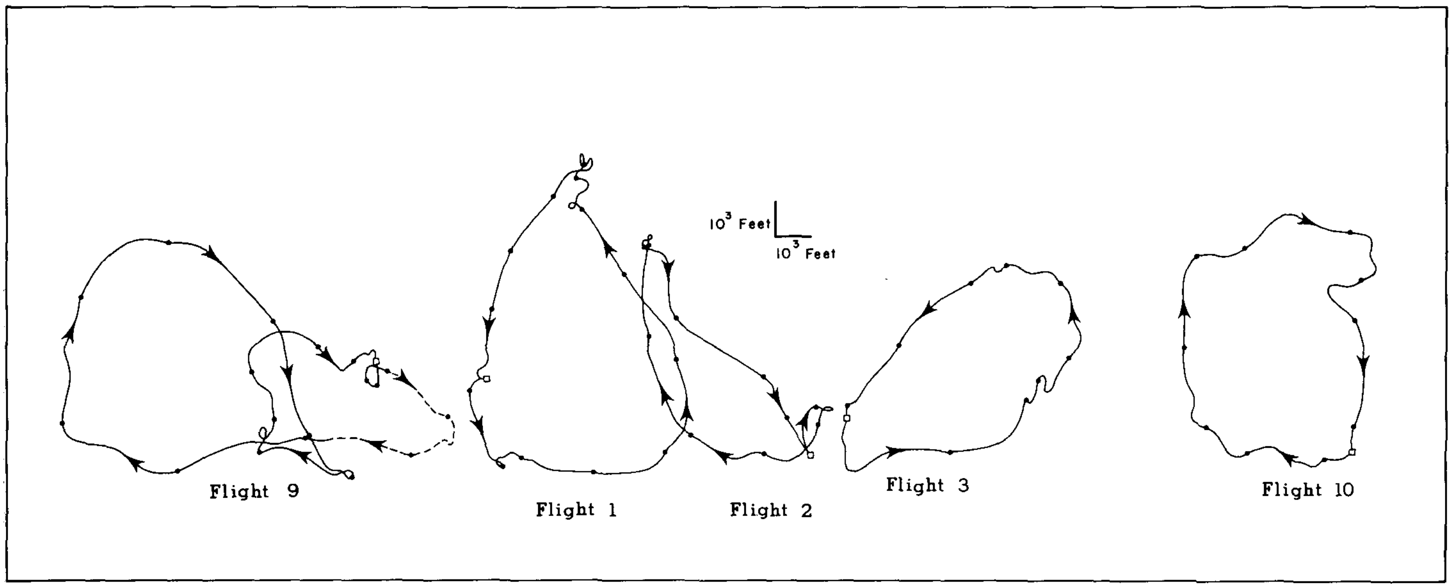

FIGURE 9.—Tetroon circulations in transverse plane (looking downstream or northward up Yucca Flat) for early-afternoon flights. Tetroon positions at 5-min. intervals. Circulation patterns ordered and spaced across the Flat in agreement with trajectory location.

or can both occur depending upon wind shear and stability conditions? For independent verification we have only flight 15 which was released during the morning hours just as the daytime vertical motion systems were becoming organized. Figure 12 shows a portion of the height trace of flight 15 (dashed line) in comparison with the height trace of a hypothetical flight up the middle of the Flat, as deduced from the vertical motion pattern of figure 11. There is general agreement in the two traces with indications of height maxima 35,000 and 65,000 ft. north of Yucca Weather Station and height minima 50,000 and 75,000 ft. north thereof. Added support for consideration of the oscillations as transverse rolls comes from the approximate agreement in ratio between mixing depth and (Lagrangian) wavelength obtained from the daytime tetroon flights (1/3.4) and the ratio of 1/2.7 specified

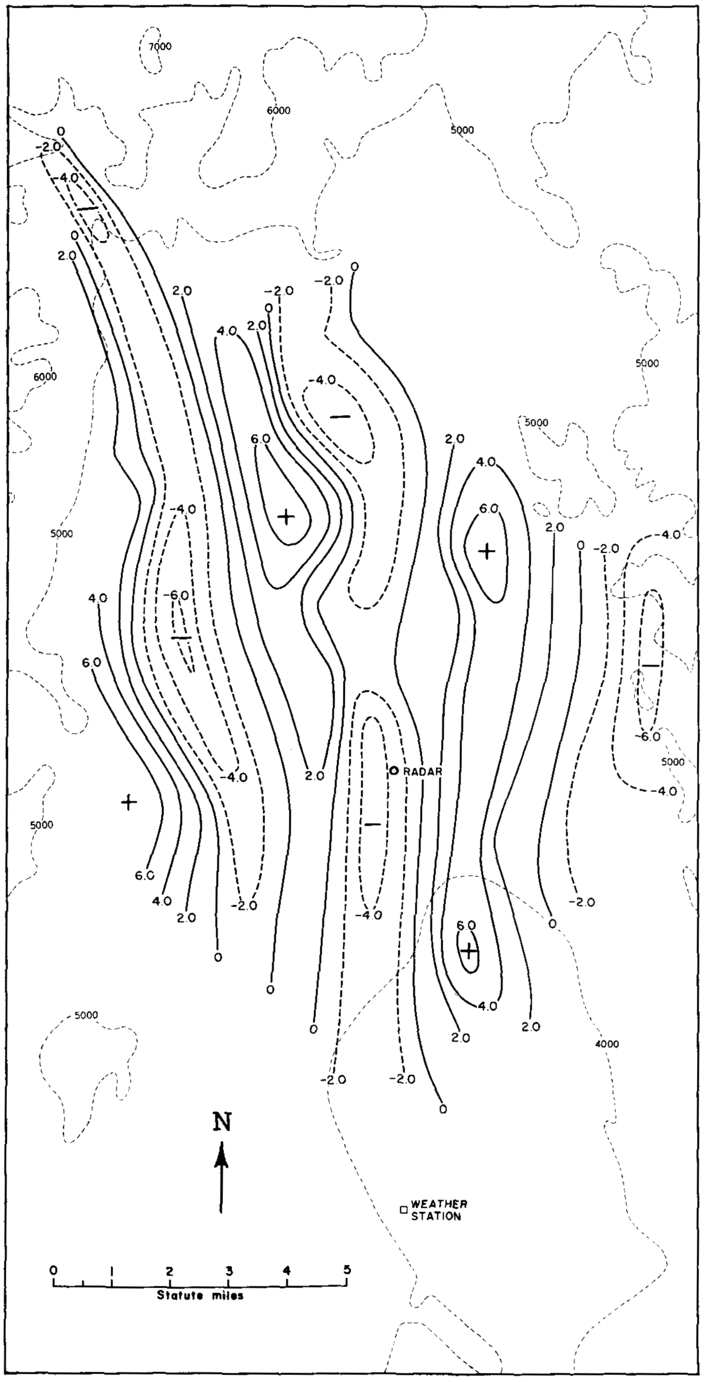

Figure 10.—Isopleths of 5-minute-average vertical motion (knots) in Yucca Flat derived from the five early-afternoon tetroon flights assuming helical (longitudinal-roll) circulation patterns.

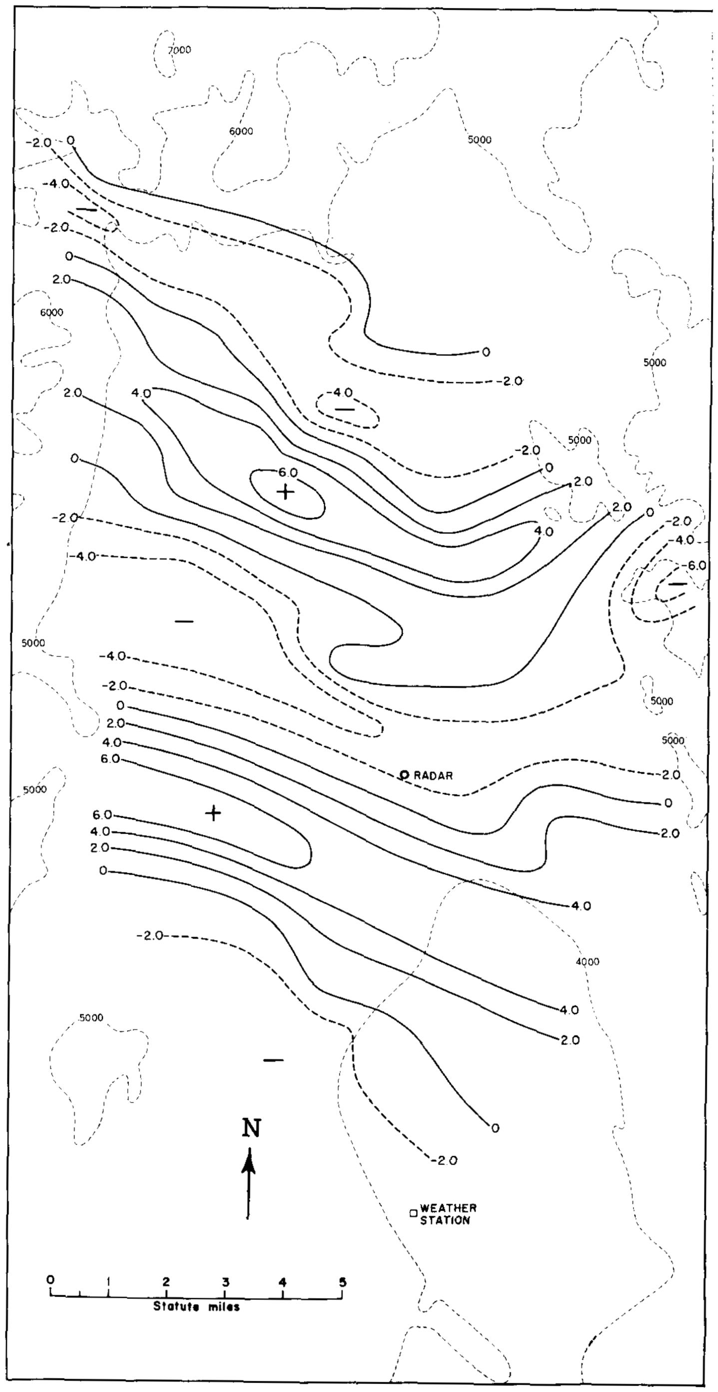

Figure 11.—Isopleths of 5-minute-average vertical motion (knots) in Yucca Flat derived from the five early-afternoon tetroon flights assuming transverse-roll circulation patterns.

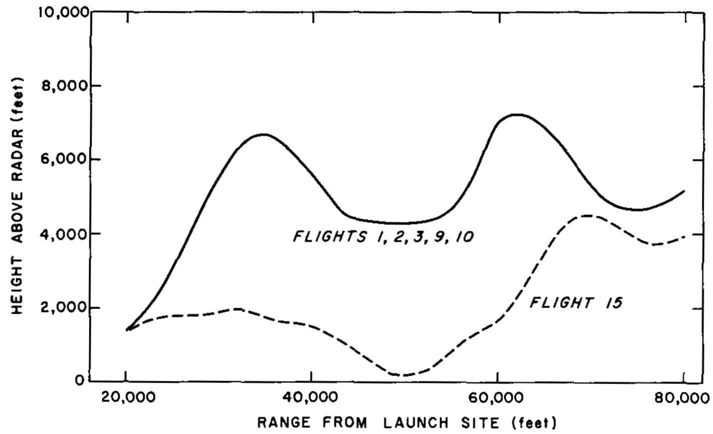

FIGURE 12.—Height trace (solid line) of hypothetical midday flight north up Yucca Flat derived from isopleth pattern in figure 11 (based on flights 1, 2, 3, 9, 10) and portion of height trace of morning flight 15 (dashed line).

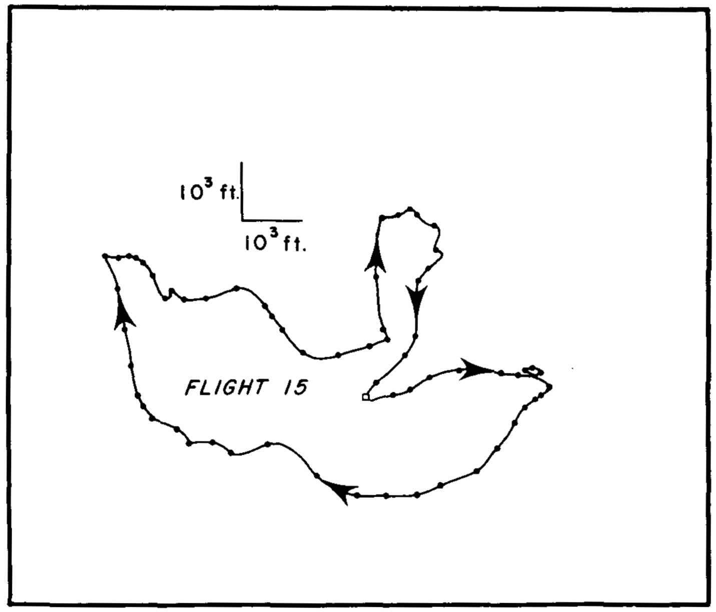

FIGURE 13.—Tetroon circulation in transverse plane (looking downstream or northward up Yucca Flat) for morning flight 15. Tetroon positions at 1-minute intervals.

by Scorer [13, p. 154] as appropriate to such rolls.* When the transverse circulation pattern of flight 15 (fig. 13) is compared with figure 9, however, the agreement is seen to be very poor because flight 15 has the opposite transverse circulation sense to flight 3 and yet the flight trajectories almost coincide. This discrepancy is not necessarily fatal to the postulation of helical circulation patterns because some east-west shift in the axes of the helices might be expected as the sun rises higher. With the data sample available the problem is moot and solution lies either in the simultaneous tracking of two or more tetroons or in the combination of the Lagrangian tetroon data with Eulerian data of the type discussed by Richter [11].

9. STATISTICS

While it is not the purpose of this paper to discuss at length velocity statistics derived from the Yucca Flat tetroon flights, it is useful to consider briefly a few vertical velocity statistics and indicate their relation to other velocity component values. Information of this type is presented in table 4. It is seen that in the mean for all the Yucca Flat flights the root mean square vertical velocity is 2.4 kt. and the turbulence intensity is 0.25, while the ratio of root mean square vertical and longitudinal, and vertical and transverse velocity components is 0.88 and 0.80 respectively. The Wallops Island data, involving overwater trajectories, gave values of 0.07, 0.80, and 0.46, respectively, for these parameters. Thus, in comparison with the overwater flights, the desert flights yield a considerably greater turbulence intensity in the vertical and show a lessening of the transverse velocity variability with respect to the vertical velocity variability, as might be expected.

*Brought to the attention of the writers by Mr. James E. Caskey, USWB.

There is considerable variation in the above values with time of day, however. Thus at Yucca Flat the ratio of root mean square vertical and longitudinal velocities varies from somewhat more than one during midday to about one-half at night, whereas the ratio of root mean square vertical and transverse velocities varies considerably less. This result is in qualitative agreement with the (Eulerian) findings of Panofsky [9] on a much smaller scale; namely, that the variability of the transverse velocity is much more dependent upon stability than is that of the longitudinal velocity so that the ratio of transverse and longitudinal variability is much larger during the day than at night.

Correlation coefficients between wind speed and vertical motion are also presented in table 4. In the mean for all flights the wind speed is stronger with descending motion than with ascending motion so that momentum is being transported downward, as would be anticipated. On some individual flights, however, momentum is being transported upward, particularly during the first day of tetroon flights.

TABLE 4.—*Vertical velocity statistics derived from Yucca Flat tetroon flights. (Height in feet, speed in knots, σ is the root mean square, R is correlation coefficient.)*

Flight	Launched (PST)	$\overline{H}$	$\overline{V}$	σ_w	$\sigma_w/\overline{V}$	σ_w/σ_{V_n}	σ_w/σ_{V_s}	$R_{V'w'}$
1	1213	6200	9.2	3.7	0.40	1.23	1.54	0.28
2	1346	4100	8.7	3.6	.41	1.24	1.33	−.02
3	1506	3100	8.6	2.9	.34	1.04	1.21	.14
6	2008	160	6.5	0.3	.05	.38	.16	.00
7	0635	1200	3.7	0.5	.13	.56	.45	−.04
9	1204	3500	12.3	3.6	.29	.74	1.16	.06
10	1456	4200	12.1	3.6	.30	.92	1.20	−.55
13	2036	150	4.2	0.5	.12	.42	.28	−.05
15	0851	2800	17.8	3.1	.17	.69	.58	−.34
Average	----------	2800	9.2	2.4	.25	.80	.88	−.06

10. CONCLUSION

While information on the nature and magnitude of vertical air motions over Yucca Flat has been obtained from these preliminary flights, much still remains to be learned about the 3-dimensional air circulation in this region. In particular:

1. It is not apparent whether the vertical circulation patterns over Yucca Flat are in the form of transverse or longitudinal rolls (helices) or whether both or neither may occur in dependence upon wind shear and stability.
2. The influence of topographic features upon the air trajectories has not been clearly delineated.
3. The transition from upslope to drainage flow, and vice versa, has not been successfully explored.

Future tetroon flights in the Yucca Flat area should provide solutions to some of these problems.

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